1 Introduction and Background

1.1 Introduction

1.1.1 Overview

Ozone is not directly emitted by pollution sources. Rather, it is a secondary pollutant and forms as a result of complex chemical processes involving sunlight and emissions of volatile organic compounds (VOCs) and oxides of nitrogen (NO_X). Naturally occurring ozone concentrations near the surface of the earth are on the order of 20-40 parts per billion (ppb). However, higher, even unhealthful, ozone concentrations can occur as a consequence of anthropogenic emissions, particularly NO_X from fuel combustion. When VOCs are weighted by their reactivity, ozone concentrations in different environments (e.g., marine, remote tropical forest, rural, urban/suburban) exhibit a strong positive relationship with NO_X and a slight positive relationship with VOCs (Seinfeld & Pandis, 1998). This is because photolysis of nitrogen dioxide (NO_2) is the only know source of oxygen atoms in the boundary layer; these oxygen atoms can combine with the abundant molecular oxygen to form ozone (O_3). The formation of ozone in the troposphere is complex because, in various chemical states, NO_X can either reduce or increase ozone concentrations. The formation of ozone is a non-linear function of its precursors which vary spatially and temporally (Finlayson-Pitts and Pitts, 2000).

The Air Resources Board following its mandate to protect the public health and welfare from the adverse effects of pollution has followed a policy of controlling both VOCs and NO_X, not only for reducing ozone but also for reducing particulate matter, acid deposition, and toxic air contaminants. As shown in Figures 1-1 and 1-2, ozone concentrations and the frequency of very unhealthful ozone concentrations have decline dramatically during the last few decades in the South Coast Air Basin (SoCAB) of California which until recently had always been the smog capital of the United States.

During the study of photochemical smog, an interesting phenomenon was observed - ozone concentrations have a tendency, particularly in urban areas, to be higher on weekends than on weekdays. The term "Weekend Effect" is a term coined by atmospheric scientists to describe this phenomenon which has been observed at many monitoring sites around the world over the last few decades. At many locations (more in recent years), ozone concentrations tend to be higher on Sunday than on Saturday; this phenomenon is called the "Sunday Effect".

This report is a compendium of the ozone Weekend Effect. It addresses past and ongoing research efforts on the Weekend Effect but focuses on presenting recent efforts by staff of the Air Resources Board. The efforts presented focus on ambient air quality data and some activity data. Incomplete work to develop emission inventories for weekend days and to conduct subsequent modeling is not presented. The report first characterizes the Ozone Weekend Effect in California. Analyses of the spatial and temporal variations of ozone and other pollutants are presented in subsequent chapters to provide insights into the causes of the Weekend Effect and the validity of various hypotheses about the factors causing the phenomenon.

1.1.2 Statement of Problem

Several studies in the past couple of decades have shown a day-of-week variation in ozone concentrations at many, though not all, monitoring sites in the South Coast Air Basin (SoCAB) and the San Francisco Bay Area Air Basin (SFBAAB). During the late-1960s and much of the 1970s, the highest ozone concentrations (Stage II and Stage III Episodes) in the SoCAB occurred most frequently on Thursdays and Fridays with Sunday having the fewest Episodes (*CARB, 1978*). A Stage II Episode occurs when a 1-hour ozone concentration is greater than or equal to 0.35 ppm. A Stage III Episode occurs when a 1-hour ozone concentration is greater than or equal to 0.50 ppm. It is interesting to note from this article that although 14 Stage III Episodes occurred between 1964 and 1977, none occurred on a weekend (see Figure 1-6). Even then already, individual sites (primarily in the western portion of the basin) would average higher ozone concentrations on Sundays than on weekdays. Over the years as ozone concentrations declined, the frequency of high ozone concentrations occurring on Sunday has increased from being the lowest of the week to being the highest of the week by the late-1990s. The term "Weekend Effect" was coined to describe this tendency for ozone concentrations to be greater on weekends than on weekdays. This phenomenon coincides with presumably lower emissions of ozone precursors, volatile organic compounds (VOCs) and oxides of nitrogen (NO_X), on the weekend. Ambient data indicate that the concentrations of carbon monoxide (CO) and NO_X decline proportionately more than the VOCs on the weekend.

Extrapolating from the Weekend Effect, some conclude that NO_X reductions could be counterproductive as an ozone control strategy in the California. However, ARB staff maintain that the pattern of variable ozone precursor reductions during the day are not representative of the uniform reduction (for all hours of the day and days of the week) that would occur under an ozone control plan. Furthermore, ozone concentrations have declined for all days of the week at all sites in the SoCAB and the SFBAAB. Although aggressive VOC control plans are in place in both of these air basins, the NO_X control plan in the SoCAB is more aggressive than the one in the SFBAAB. In addition, ozone concentrations have not declined significantly in the Central Valley. Data from areas with different meteorology, mix of emission sources, and control programs may help illucidate the weekend effect; for example, in clean areas (e.g., background ozone concentrations and infrequently impacted by pollution transport), one would expect no difference between ozone concentrations on weekdays and weekends. In NO_X-limited areas, one might expect the lower NO_X on weekends to result in lower ozone concentrations on weekends. In VOC-limited areas, one might expect the lower NO_X on weekends to result in higher ozone concentrations on weekends. However, the changes might not occur as expected because both VOC and NO_X are being reduced but not uniformly at all locations.

In response to the Board's directive at its November 5, 1998 hearing, the staff undertook research efforts to explain the Weekend Effect. The objectives of the research were to organize and analyze the available information to better understand the nature of the ozone Weekend Effect and to identify its likely causes. These causes need to be examined for the implications of pollution control strategies.

Assuming that meteorology is invariant with day of the week, the fact that human activity patterns are different on different days of the week is the only reasonable explanation for the weekend effect. However, incomplete knowledge of these changing activity patterns is only a partial explanation of our inability to state the cause of the Weekend Effect with certainty. Pollutants are emitted at different times and locations, and subject to the effects of meteorology (e.g., dispersion, dilution, deposition) and photochemistry to generate ozone and particulate matter. To identify the cause(s) of the Weekend Effect, the temporal and spatial patterns of emission activity, the overall emission inventory, meteorology, and photochemistry will need to be woven together.

CARB staff has proposed four hypotheses of the cause of the Weekend Effect: 1) NO_X-Reduction (NO_X-Disbenefit) Hypothesis, 2) NO_X-Timing Hypothesis, 3) Carryover (at ground-level and aloft) Hypothesis, and 4) Increased Weekend Emissions Hypothesis. These hypotheses are discussed in detail in Chapter 3. The results of various analyses of ambient air quality and activity data are used to characterize day-of-week patterns and to evaluate for consistency with the hypotheses. Each of these hypotheses includes multiple disciplines that need to be integrated and corroborated in the process of isolating the factors contributing to the Ozone Weekend Effect.

Many of the analyses in this report focus on the South Coast Air Basin (please refer to Figure 1-4 for a map highlighting the relative location of the SoCAB to the State and other air basins). The dense monitoring network of the SoCAB, the long historical record of air pollution monitoring, the high pollutant concentrations, and its large population make this area the focus of most air quality analyses into the cause(s) of the Ozone Weekend Effect. A map displaying topographic features and county boundaries of the SoCAB is provided in Figure 1-5. A map portraying the transportation network of freeways and highways in the SoCAB as well as the core set of monitoring sites that will be referred to in many chapters is presented in Figure 1-6.

Although this report does not delve into weekday/weekend emission differences because current data are limited, Table 1-1 is provided to indicate the relative strength of the various emission source categories. Note that mobile sources are the dominant source category of Reactive Organic Gases (ROG), oxides of nitrogen (NO_X), and carbon monoxide (CO) emissions in the SoCAB. Also note that the contribution of heavy-duty trucks is very significant for NO_X but much less so for ROG and CO.

1.2 Background

Air quality scientists have always expected that emission control programs would interact with non-linear photochemistry to produce local effects of short duration inconsistent with the general trend of ozone reduction. In 1972, southern California coastal sites, Lennox, Long Beach, and Whittier, had higher ozone on weekend days. This was true although emissions were lower during the weekend days. For other sites, ozone behavior did not distinguish between weekday and weekend days. Between 1972-73, early in the morning, all southern California sites had higher ozone concentrations on weekend days than on weekdays, *(Levitt and Chock, 1976*). California's emission control program, then uniquely in the nation, advocated control of both non-methane hydrocarbons (NMHC) and nitrogen oxides (NO_X) emissions. From weekdays to weekends, NO_X concentrations (and presumably emissions) are reduced more than NMHC concentrations (emissions). The Weekend Effect has since been hypothesized as a side effect of too much NO_X emissions control (i.e., NO_X-Disbenefit Hypothesis). Nevertheless, ARB's control program has substantially lowered ozone concentrations from 1972-73 levels.

Geographic and temporal outlines of the southern California "Weekend Effect" have changed over time. Between 1984-86, coastal areas experienced higher ozone concentrations during Saturdays and Sundays while inland areas had highest ozone concentrations during Saturdays (*Zeldin and Horie, 1989*). While the geographic area of the Day-of-the-Week effect did grow, ozone concentrations on Saturdays, rather than Saturdays and Sundays, became the highest of the week in the heavily impacted downwind areas of southern California. Emission control program remained steady reducing hydrocarbons and NO_X emissions simultaneously. [By any measure?], our control program has substantially lowered ozone concentrations from 1984-86 levels.

We commissioned the University of California, Los Angeles (UCLA), to conduct two long-term studies of the southern California Day-of-the-Week effects with particular emphasis on control strategy implications. The first UCLA study analyzed data from 1986 to 1993 (*Blier and Winer, 1996*). Highest daily peak ozone concentrations occurred significantly more often on Thursdays through Saturdays than on Sundays through Wednesdays. Ozone concentrations within each region related more strongly to NO_X concentrations within that region than to the basin NO_X values. Surface carryover of NO_X did not strongly affect Day-of-the-Week effects ("Carryover" Hypothesis). Yet, the ten highest daily hourly-average ozone concentrations [BY SITE?] showed the most pronounced decrease in areas of maximum percentage decrease in early morning NO_X concentrations. Trend analyses indicated that regardless of the meteorological conditions, generally lower peak ozone values were observed in the latter four years (1986-1989) than in the first four years (1990-1993). By various measures, ARB's control program substantially lowered ozone concentrations from 1990-93 levels.

The second UCLA study analyzed data from 1986 to 1996 and expanded the analysis to aerosols and particulate matter data (*Blier and Winer, 1999*). Carryover of NO_X was of greater significance from Friday evening to Saturday than for other days of the week. Limited ground observations suggested a weak carryover effect for NO_X and NO_2. The day-of-the-week effect did not provide evidence that further NO_X control would be counterproductive to further ozone reductions. During 1994-5 Saturdays and Sundays, concentration reductions of NMHC and NO_X coincided with increases in ozone. However, 1986-96 ozone concentrations declined significantly coincident with significant reductions in levels of NMHC and NO_X. A weak Day-of-the-Week influence was noted for aerosol concentrations and ambient temperatures, indicating some impact attributed to human activities. Additionally and critically, the study observed a shift to later and shorter ozone seasons, with Sunday becoming the highest ozone peak day-of-the-week. Once again, the ozone control program of combined VOC and NO_X emission reductions substantially lowered ozone concentrations from 1996 levels.

During the last three decades, geographic and temporal outlines of Day-of-the-Week effect in southern California have changed. The emission control program has continuously focused on simultaneous control of VOC and NO_X during the same period, and by almost any measure, the dual control program has substantially reduced ozone concentrations.

References

Blier W., A.M. Winer, D. Hansen, and N. Verma (1996) “Characterization of ozone episodes in the south Coast Air Basin: Effects of air parcel residence time and weekend/weekday differences,” Final Report, Contract No. 93-316, California Air Resources Board, June 28. (http://www.arb.ca.gov/aqd/weekendeffect/ucla1.htm)

Blier W., A.M. Winer, D. Hansen, and R. Chavira (1999) “Analysis of weekend/weekday differences in ambient air quality and meteorology in the South Coast Air Basin,” Final Report to California Air Resources Board, Contract No. 95-334, June 1. (http://www.arb.ca.gov/aqd/weekendeffect/ucla2.htm)

California Air Resources Board (1978) "Ozone Episode Experience in the South Coast Air Basin," California Air Quality Data, January-February-March, Vol. X, 1:2-7.

Finlayson-Pitts, B. and Pitts, J. Jr. (2000), *Chemistry of the Upper and Lower Atmosphere - Theory, Experiments, and Applications*, Academic Press, San Diego.

Levitt, S. and D. Chock (1976) “Weekday-weekend pollutant studies of the Los Angeles Basin,” *Air Pollution Control Association Journal*, **26:** 1091-1092.

Seinfeld, J.H. and S. Pandis (1998), *Atmospheric Chemistry and Physics - from Air Pollution to Climate Change*, John Wiley and Sons, Inc., New York.

Zeldin, M., Y. Horie, and V. Mirabella (1989) “An analysis of weekend/weekday differences in the South Coast Air Basin of California,” Paper 89-125.6, Air & Waste

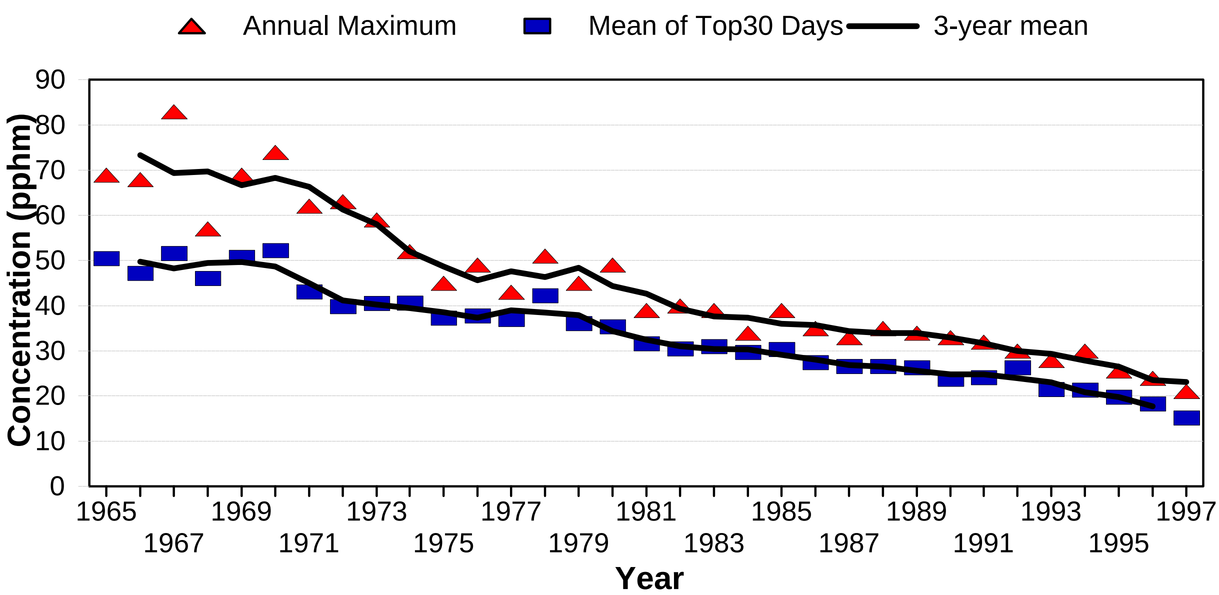
Management Association 82nd Annual Meeting & Exhibition, June 25-30, 1989, Anaheim, CA.

Table 1-1. Annual average emissions of ROG, NO_X, and CO (tons/day) by source category in the South Coast Air Basin, 1995 and 2000

	ROG		NO_X		CO	
Source Category	**1995**	**2000**	**1995**	**2000**	**1995**	**2000**
Stationary Sources	275	279	144	118	71	66
Area-Wide Sources	228	200	31	34	716	633
Mobile Sources:	1031	730	1045	844	9653	6525
Heavy-Duty Trucks	41	36	328	348	431	302
Other Vehicles	990	694	718	496	9223	6223
Other Mobile Sources	108	108	270	268	870	808
Natural Sources	n/a	4	n/a	5	n/a	106

NOTE: All figures are derived from CEFS 1996 Base Year Forecast Scenarios for 2000 Almanac; however, figures for Mobile Sources are from Emfac 2000 (v 1.99), where heavy-duty trucks include all trucks weighing 8500 pounds and up.

Figure 1-1. Trends of peak ozone concentrations observed in the South Coast Air



Basin, 1965 - 1999

Figure 1-2. Number of days per year when Stage I ozone episode occurred within the South Coast Air Basin, 1965 - 1999

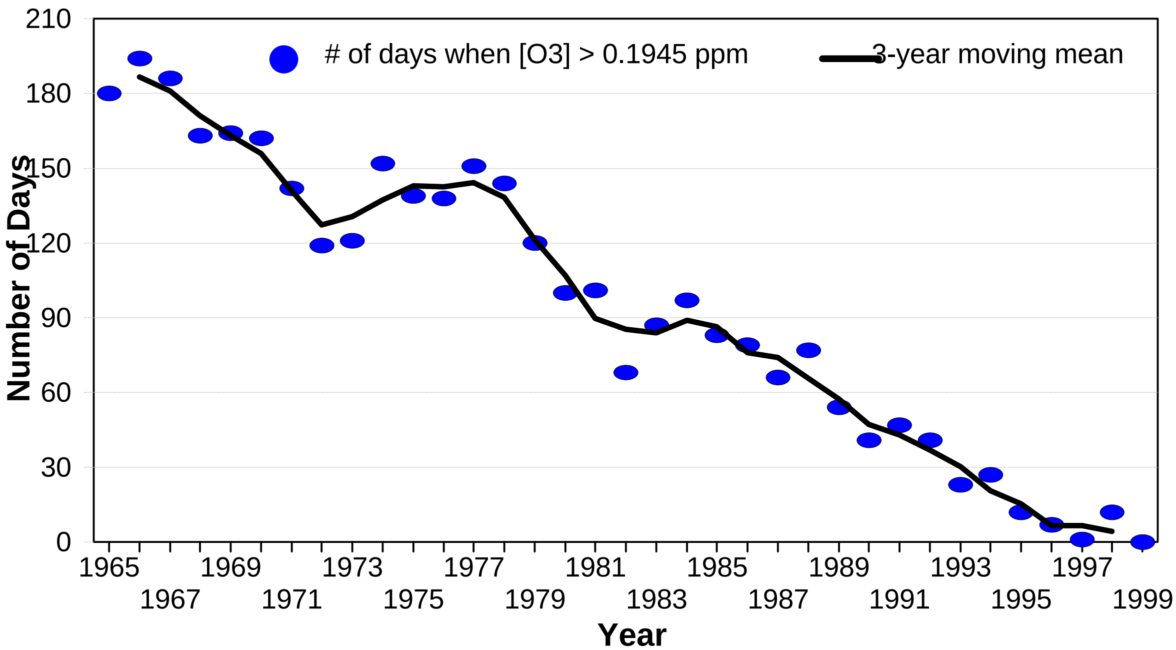


Figure 1-3. Frequency of Stage II and Stage III ozone episodes by day of the week in the South Coast Air Basin, 1964 - 1977.

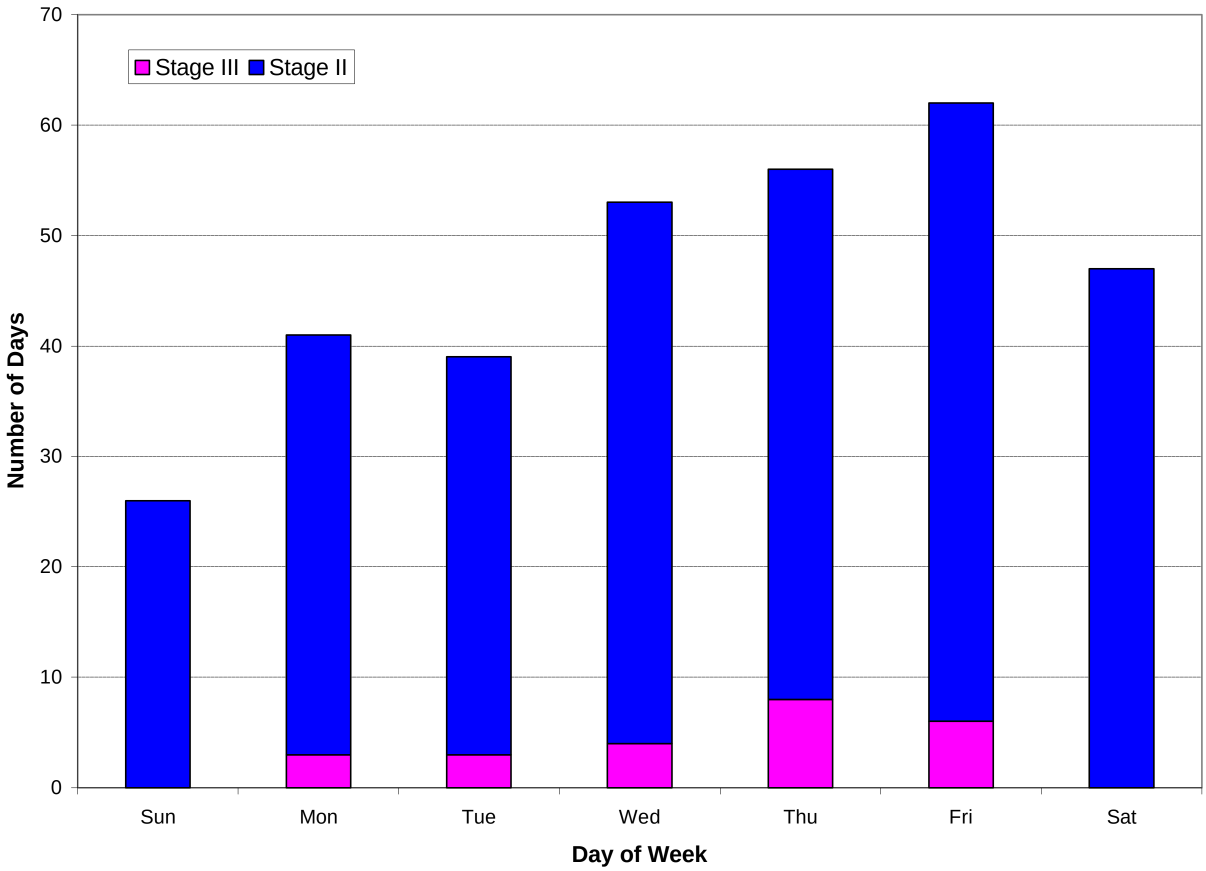


Figure 1-4. Outline of the State of California showing the boundaries of air basins. The South Coast Air Basin, the focus of most analyses in this report, is highlighted to show its location and size relative to the other 14 air basins in California.

Figure 1-5. Map showing the topographic features, counties, and major regions in and around the South Coast Air Basin.

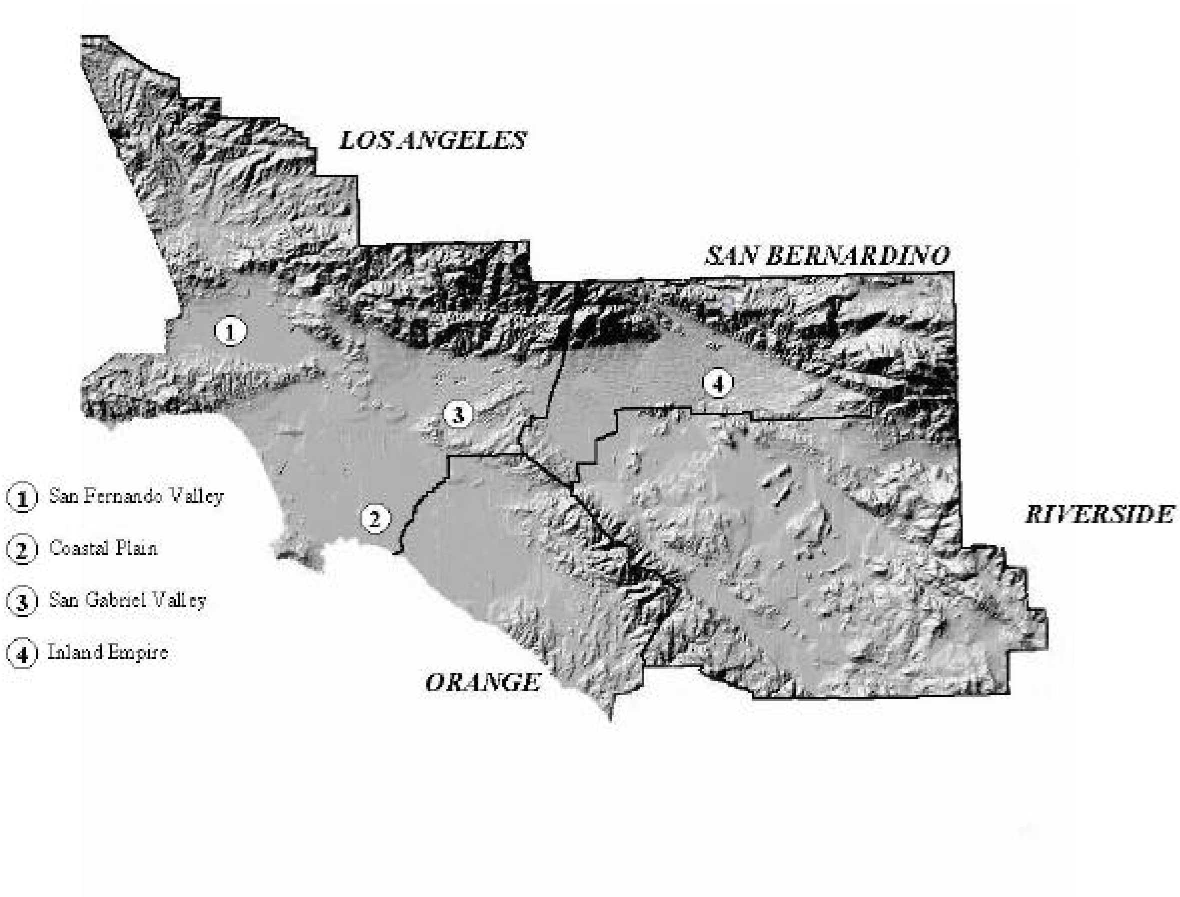


Figure 1-6. Map showing the major freeways and highways in the South Coast Air Basin as well as the locations of the "core" monitoring sites presented in many of the chapters of this report.